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Evidence for the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$

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Abstract

A study of transitions between Υ states with the emission of charged pions using 398 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric energy e^+e^- collider is presented. A clear peak from the decay $\Upsilon(1S) \to \mu^+\mu^-$ is observed in the invariant mass distribution of $(\mu^+\mu^-)$ pairs from the $(\mu^+\mu^-\pi^+\pi^- X)$ event sample. The mass difference distribution $(M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ for $M_{\mu^+\mu^-}$ from the $\Upsilon(1S)$ mass region has two peaks from $\Upsilon(2S,3S) \to \Upsilon(1S)\pi^+\pi^-$ decays, with no background. A third peak at $\Delta M = (1119.0 \pm 1.4)$ MeV/c^2 can be interpreted as evidence of a signal from the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ with a subsequent $\Upsilon(1S) \to \mu^+\mu^-$ transition. This is the first example of a non-$B\bar{B}$ decay of the $\Upsilon(4S)$ resonance. The preliminary estimated branching fraction is equal to $\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (1.1 \pm 0.2(\text{stat.}) \pm 0.4(\text{sys.})) \times 10^{-4}$.

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INTRODUCTION

The bottomonium state $\Upsilon(4S)$ has a mass above the threshold for $B\bar{B}$ pair production and decays mainly into these B-meson pairs ($\mathcal{B}(\Upsilon(4S) \to B\bar{B}) >96\%$ [1]). The decay modes $\Upsilon(4S) \to \Upsilon(mS)\pi\pi$ with m =1, 2, 3 should exist. These decays are analogous to the decay modes of the low lying Υ states [2]. Upper limits on the branching fractions of $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(4S) \to \Upsilon(2S)\pi^+\pi^-$ decays have been set by the CLEO experiment [3]. Similar decay modes of the charmonium state $\psi(3770)$, which has a mass above the $D\bar{D}$ production threshold have been observed recently [4].

In this paper we report the first evidence for the decay mode $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ from the Belle experiment.

EVENT SELECTION

In this study 398 fb^{-1} of data collected by the Belle detector [5] on the $\Upsilon(4S)$ resonance and in the nearby continuum is used. Well reconstructed charged particles and photons are used to reconstruct the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ with the subsequent leptonic decay $\Upsilon(1S) \to \ell^+\ell^-$.

Several selection criteria for charged tracks and neutral particles in an event were applied. Charged particle candidates were required to satisfy the following requirements:

- transverse momentum, $p_{\mathrm{t}} >$30 MeV/c;
- impact parameter transverse to the beam, $dr <$3 cm;
- impact parameter along the beam axis, $dz <$4 cm;
- tracks that are not identified as a decay product of a reconstructed secondary V^0.

Charged particles are identified by combining responses from the CDC, TOF and ACC subdetectors of Belle [5] into a likelihood $\mathcal{L}_i$ [6, 7] where i indicates the particle type (e, μ, π, K, p). A charged particle is identified as an electron if the corresponding likelihood ratio, $P_e >$0.9 [6], or if the electron mass hypothesis has the highest probability. The electron detection efficiency for $P_e >$0.9 is approximately 90% for single electrons embedded onto hadronic events and uniformly distributed over the polar angle range $35^\circ \leq \theta \leq 125^\circ$ and the momentum range 0.5 GeV/$c \leq p \leq$3.0 GeV/c. Charged particles are identified as muons if the corresponding muon likelihood ratio is $P_\mu >$0.8. The muon detection efficiency above a given likelihood threshold is approximately 91.5% for the single-track simulated muons uniformly distributed over the polar angle range $20^\circ \leq \theta \leq 155^\circ$ and the momentum range 0.7 GeV/$c \leq p \leq$3.0 GeV/c. Charged particles that are not identified as muons or have a likelihood ratio $P_e <$0.05 were considered as pions.

The identification of γ's and π^0's is based on information from the electromagnetic calorimeter. Calorimeter clusters not associated with reconstructed charged tracks are considered as γ candidates. In addition, these electromagnetic clusters must have energies greater than 50 MeV and not satisfy the π^0 hypothesis when combined with another photon in the event.

Two electromagnetic showers with an invariant mass $|M_{\gamma\gamma} - m_{\pi^0}| <$8 MeV/$c^2$ (where m_{π^0} is the nominal π^0 mass) form a π^0 if the confidence level for their kinematic fit to

the π^0 hypothesis is greater than 0.1 and if their reconstructed momentum is greater than 100 MeV/c.

Hadronic events are selected by the standard Belle hadronic selection. The most important of these selection criteria are the following: multiplicity of charged tracks in an event $N_{\rm ch} \geq 3$; the electromagnetic calorimeter cluster multiplicity $nECL > 1$; the event's visible energy $E_{\rm vis} \geq 0.2\sqrt{s}$, where $\sqrt{s}$ is a center of mass energy; the energy sum of good cluster energies in the electromagnetic calorimeter must satisfy $0.18 \leq E_{\rm sum}/\sqrt{s} \leq 0.8$; the sum of the z components of each charged track's and photon's momenta is required to satisfy $|P_{\rm z}| < 0.5\sqrt{s}$.

Events with a pair of oppositely charged particles and with an invariant mass $M_{\rm ch^+ch^-} > 9$ GeV/c^2 were selected from the hadronic sample. The invariant mass distribution for these events in the on-resonance sample is shown in Fig. 1. The $M_{\mu^+\mu^-}$ invariant mass distribution when both particles are muons is also shown in Fig. 1. An enhancement near the $\Upsilon(1S)$ mass can be observed.

The peak at the invariant mass $\sim$10.6 GeV/c^2 originates from the process $e^+e^- \to \mu^+\mu^-(e^+e^-(\gamma))$. About 60% of the events in the $M_{\rm ch^+ch^-}$ spectrum come from identified $\mu^+\mu^-$ pairs. The absence of e^+e^- events with high invariant mass is mainly due to selection criterion for the energy sum of good cluster energies in the electromagnetic calorimeter $E_{\rm sum}/\sqrt{s} \leq 0.8$. Therefore we restrict our attention to $\mu^+\mu^-$ pairs.

To reduce the background from poorly reconstructed events we impose an additional requirement on the visible energy of selected events: 10.5 GeV $< E_{\rm vis} <$ 12.5 GeV. After all cuts described above about 112.5k events were selected.

ANALYSIS

To reconstruct $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ decays, which in addition to the decay products of the $\Upsilon(1S)$ contain two charged pions in the final state, $\mu^+\mu^-\pi^+\pi^-X$ events were considered. This additional selection criterion reduces the primary sample of events considerably (by about a factor of 100). The number of selected events is 957. The muon pair invariant mass distribution, $M_{\mu^+\mu^-}$, for the $\mu^+\mu^-\pi^+\pi^-X$ events is shown in Figs. 1 and 2. The clear low background signal for $\Upsilon(1S) \to \mu^+\mu^-$ is shown in Fig. 2.

The fit to this distribution using a sum of the Crystal Ball function [8] for the signal and a polynomial function for the background results in the peak position $M_{\mu^+\mu^-}$(peak)=(9454.7 ± 5.5) MeV/c^2, which is consistent with the nominal $\Upsilon(1S)$ mass value $M_{\Upsilon(1S)}$=(9460.30 ± 0.26) MeV/c^2 [1].

To observe resonance states that decay into the $\Upsilon(1S)$ $\pi^+\pi^-$ final state the distribution of the mass difference $\Delta M = (M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ where $M_{\mu^+\mu^-}$ is restricted to $|M_{\mu^+\mu^-} - M_{\Upsilon(1S)}| < 6$ MeV/c^2 was examined (see Fig. 3). Here $M_{\Upsilon(1S)}$ is the nominal $\Upsilon(1S)$ mass. To reduce background from $\Upsilon(1S)$ production in radiative return processes [9] with the subsequent conversion of the emitted photon as an electron-positron pair ($\gamma* \to e^+e^-$), which is then misidentified as $\pi^+\pi^-$, we impose an additional requirement on the angle between the pion momenta in the lab system, $\cos\theta_{\pi\pi} < 0.95$, on the events shown in Fig. 3. The $\cos\theta_{\pi\pi}$ distributions for the events in the peaks and in the sideband regions are shown in Fig. 4. The peaks near $\cos\theta_{\pi\pi} = 1$ are from the radiative return $\Upsilon(1S)$ background described above. The additional $\cos\theta_{\pi\pi}$ requirement removes this background.

Three peaks are seen in the ΔM distribution (Fig. 3). The first (second, third) peaks have values of $\Delta M \sim 0.56(0.89, 1.12)$ GeV/c^2, respectively.

The first and second peaks have little or no background. They originate from the decays $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ with a subsequent $\Upsilon(1S) \to \mu^+\mu^-$ transition, respectively. Fits to the first two peaks using a Gaussian (see Fig. 5a,b) result in the following values of the peak positions $\Delta M(1\text{st}) = (562.0 \pm 0.1)$ MeV/c^2, $\Delta M(2\text{nd}) = (893.5 \pm 0.2)$ MeV/c^2. The mass difference between $\Upsilon(2S)$, $\Upsilon(3S)$ and the $\Upsilon(1S)$ states presented in PDG [1] is $(M_{\Upsilon(2S)} - M_{\Upsilon(1S)}) = (563.0 \pm 0.4)$ MeV/c^2, $(M_{\Upsilon(3S)} - M_{\Upsilon(1S)}) = (894.9 \pm 0.6)$ MeV/c^2, respectively. The values obtained from the fits to the distributions in Fig. 5a,b by Gaussian functions are compatible with the corresponding PDG values. The χ^2/NDF for the first and second peaks are 1.4 and 1.8, respectively. The small differences between the mean values obtained from the Gaussian fits and the PDG values can be explained by systematics due to the imperfect modeling of the ΔM distributions. We conclude that the first and second peaks are produced by the decays $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$.

STUDY OF THE THIRD PEAK

In contrast to the first two peaks, the third peak has a considerably larger background. The position of the peak is derived from a fit to the distribution in Fig. 6 using a Gaussian for the signal and a polynomial function for the background to be, $\Delta M = (1119.0 \pm 1.4)$ MeV/c^2, which is in good agreement with the mass difference $(M_{\Upsilon(4S)} - M_{\Upsilon(1S)}) = (1120.0 \pm 3.5)$ MeV/c^2 from the PDG [1]. The signal above background is determined from the fit to be, $N_{\text{ev}} = (38.0 \pm 6.9)$, with a statistical significance of 7.3 standard deviations. This peak is interpreted as a signal from the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ with a subsequent $\Upsilon(1S) \to \mu^+\mu^-$ transition.

Using the off-resonance sample ($\sqrt{s}$=10.52 MeV, integrated luminosity $\int \mathcal{L}dt \simeq 40$ fb^{-1}), the mass difference distribution shown in Fig. 7 shows only two peaks, which are from $\Upsilon(2S)$, $\Upsilon(3S)$ decays. The enhancement at ΔM =1060 MeV/c^2 in this distribution is compatible with the background level near the third peak in the on-resonance sample (Fig. 3) and lower than the luminosity scaled yield of the third peak in the on-resonance data. For the renormalized on-resonance sample the total number of events and background in the interval 1.11 GeV/$c^2 < \Delta M <$1.135 GeV/c^2 corresponding to the third peak is $N_{\text{tot}}^{\text{res}} = (5.4 \pm 0.8)$, $N_{\text{bkg}}^{\text{res}} = (1.1 \pm 0.4)$ respectively. The number of events in the shifted interval for the off-resonance sample is $N_{\text{tot}}^{\text{cont}} = (2.0 \pm 1.4)$. Unfortunately the low statistics of the off-resonance sample preclude using it to subtract background in the on-resonance sample.

However, additional information can be obtained from the study of the $\pi^+\pi^-$ system. The invariant mass distribution of the $\pi^+\pi^-$-system $M_{\pi^+\pi^-}$ for events from the observed peaks and background is shown in Figs. 8a-d. These distributions are directly compared with model predictions as the efficiency corrections are negligible. The background, which is small, is not subtracted from the $M_{\pi^+\pi^-}$ distributions for the three observed peaks (Figs. 8a-c).

The $M_{\pi^+\pi^-}$ distribution for the first peak ($\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ decay) is well described by the Yan model [10], where the hadronic transition between heavy quarkonia is considered as a two-step process: the emission of gluons from heavy quarks and subsequent conversion of these gluons into light hadrons. This transition can be described in the context of a "multipole" expansion scheme where the gluon fields are expanded in a multipole series.

The $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decay distribution (Fig. 8b) on the other hand is described by the Moxhay model [11]. In this model the decay proceeds through coupling to $B\bar{B}$, $B^*\bar{B}^*$,

..., intermediate states [12].

This significant coupling to the flavored sector is motivated by the fact, that the $\Upsilon(3S)$ lies closer to the open $B\bar{B}$ production threshold than the $\Upsilon(2S)$. This decay mechanism causes a double peak structure in the $M_{\pi^+\pi^-}$ distribution. The multipole and coupled-channel amplitudes interfere in the Moxhay model.

The above models were already used successfully by the CLEO experiment [13] to describe the $M_{\pi^+\pi^-}$ distributions in the $\Upsilon(2S,3S) \to \Upsilon(1S)\pi^+\pi^-$ decays. The $M_{\pi^+\pi^-}$ distribution for the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ (Fig. 8c) is better described by the Yan model.

The distributions for all resonance decays (Fig. 8a-c) show an enhancement at high masses. In contrast in the $M_{\pi^+\pi^-}$ distribution for the background (events out of peak ranges, i.e. from the mass difference ranges 0.3 GeV/c^2 < ΔM <0.555 GeV/c^2, 0.57 GeV/c^2 < ΔM <0.885 GeV/c^2, 0.905 GeV/c^2 < ΔM <1.11 GeV/c^2, 1.135 GeV/c^2 < ΔM <1.4 GeV/c^2) the high mass region is significantly suppressed (see Fig. 8d). This difference in the behaviour of the $M_{\pi^+\pi^-}$ distribution is an additional argument in favour of a resonance interpretation for the third peak.

The branching fraction for the $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ decay was extracted from $\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = N_{\rm ev}/(N_{\rm ev}^{\rm tot} \cdot \varepsilon \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-))$. The total number of $\Upsilon(4S)$ in the data sample is $N_{\rm ev}^{\rm tot} = (386 \pm 5) \times 10^6$, the nominal branching fraction $\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 2.48\%$. The EvtGen event generator [14] with a matrix element taking into account particle spins was used for the Monte Carlo simulation of $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ events. The Monte Carlo generated events were then passed through the detector simulation and reconstruction programs. The efficiency of the event reconstruction is then obtained from the Monte Carlo sample to be $\varepsilon = 0.035$. The systematic uncertainty on the reconstruction efficiency is estimated by comparing the number of reconstructed $\Upsilon(2S,3S)$ events with the number of events that were calculated for the radiative return process $e^+e^- \to e^+e^-\gamma \to \Upsilon(2S,3S)\gamma$ in the model [15]. The difference is 35% and is a conservative estimate of the event reconstruction uncertainty. Another systematic uncertainty comes from the poor knowledge of the $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ decay matrix element. This was estimated from a comparison of the previously calculated efficiency ε with the efficiency calculated with a phase space matrix element and this systematic uncertainty results in 8%.

The preliminary result for the branching fraction is $\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (1.1 \pm 0.2(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-4}$. The width, Γ, of the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ is (2.2 ± 1.0) keV, which is comparable with $\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-) = (8.1 \pm 1.2)$ keV and $\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-) = (1.2 \pm 0.2)$ keV.

CONCLUSIONS

A study of transitions between Υ states with the emission of charged pions at Belle has been performed. A clear peak from the $\Upsilon(1S) \to \mu^+\mu^-$ decay in the invariant mass distribution of $(\mu^+\mu^-)$ pairs from the $\mu^+\mu^-\pi^+\pi^-X$ event sample is observed. The mass difference distribution $(M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ for $M_{\mu^+\mu^-}$ from the $\Upsilon(1S)$ mass region has two peaks from '$\Upsilon(2S,3S) \to \Upsilon(1S)\pi^+\pi^-$ decays with no background. A third peak at $\Delta M = (1119.0 \pm 1.4)$ MeV/c^2 is interpreted as evidence of a signal from the decay $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ with a subsequent $\Upsilon(1S) \to \mu^+\mu^-$ transition. The preliminary estimated branching fraction results in $\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (1.1 \pm 0.2(\text{stat.}) \pm 0.4(\text{sys.})) \times 10^{-4}$.

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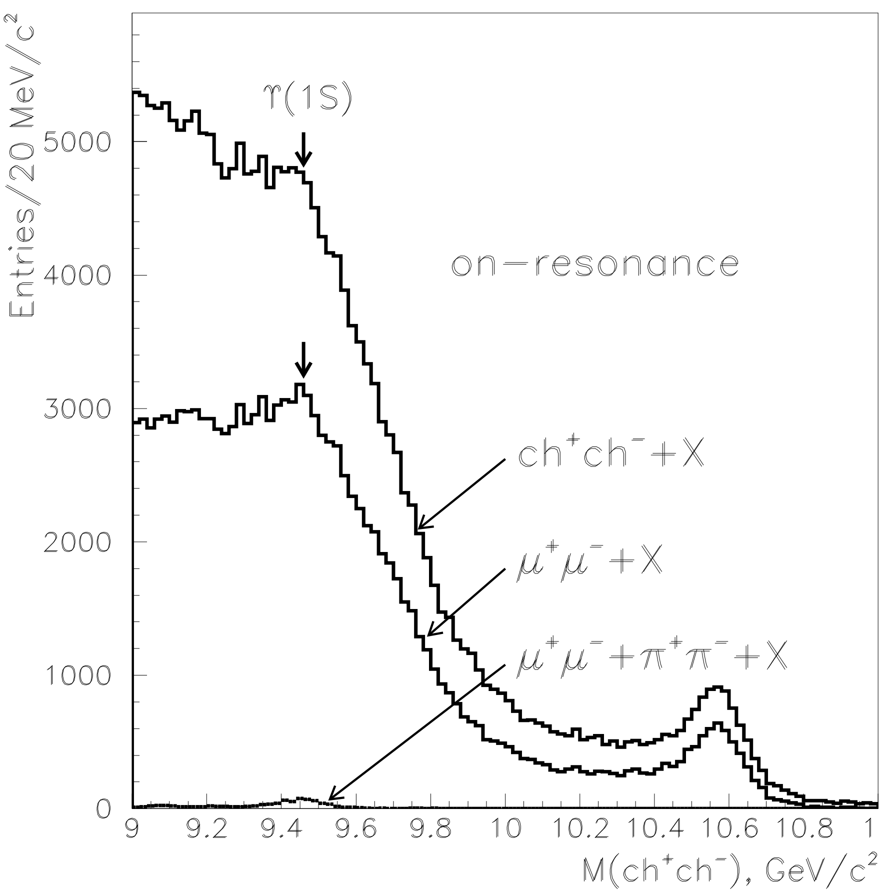

FIG. 1: The invariant mass distribution of charged particle pairs $M_{\mathrm{ch}^+\mathrm{ch}^-}$ for the standard Belle hadronic on-resonance sample.

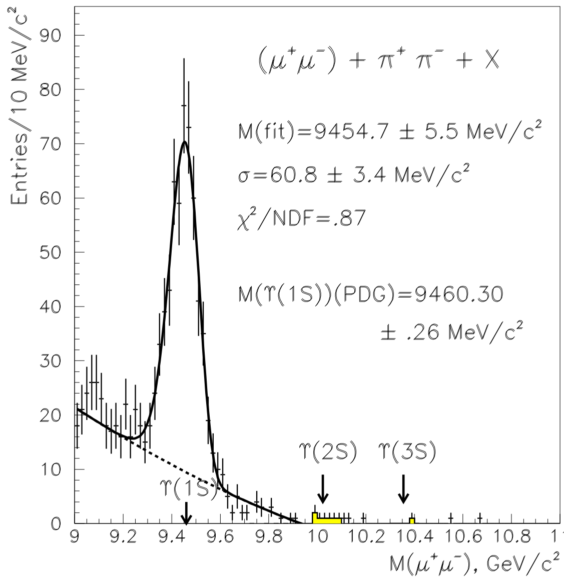

FIG. 2: The invariant mass distribution of muon pairs $M_{\mu^+\mu^-}$ in $\mu^+\mu^-\pi^+\pi^-X$ events fitted with the sum of a Crystal Ball and polynomial function.

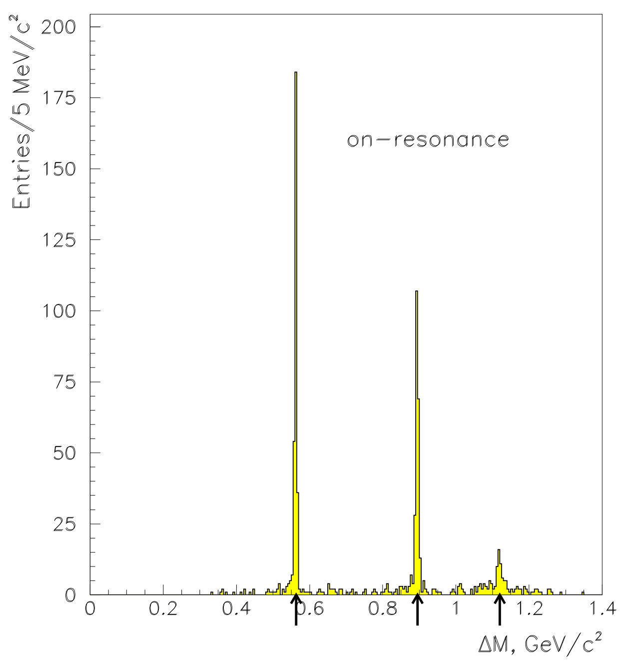

FIG. 3: The mass difference $\Delta M = (M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ distribution where $M_{\mu^+\mu^-}$ lies in the $\Upsilon(1S)$ mass region. Arrows show the positions of the mass differences $(M_{\Upsilon(2S)} - M_{\Upsilon(1S)})$, $(M_{\Upsilon(3S)} - M_{\Upsilon(1S)})$ and $(M_{\Upsilon(4S)} - M_{\Upsilon(1S)})$ from PDG [1], respectively.

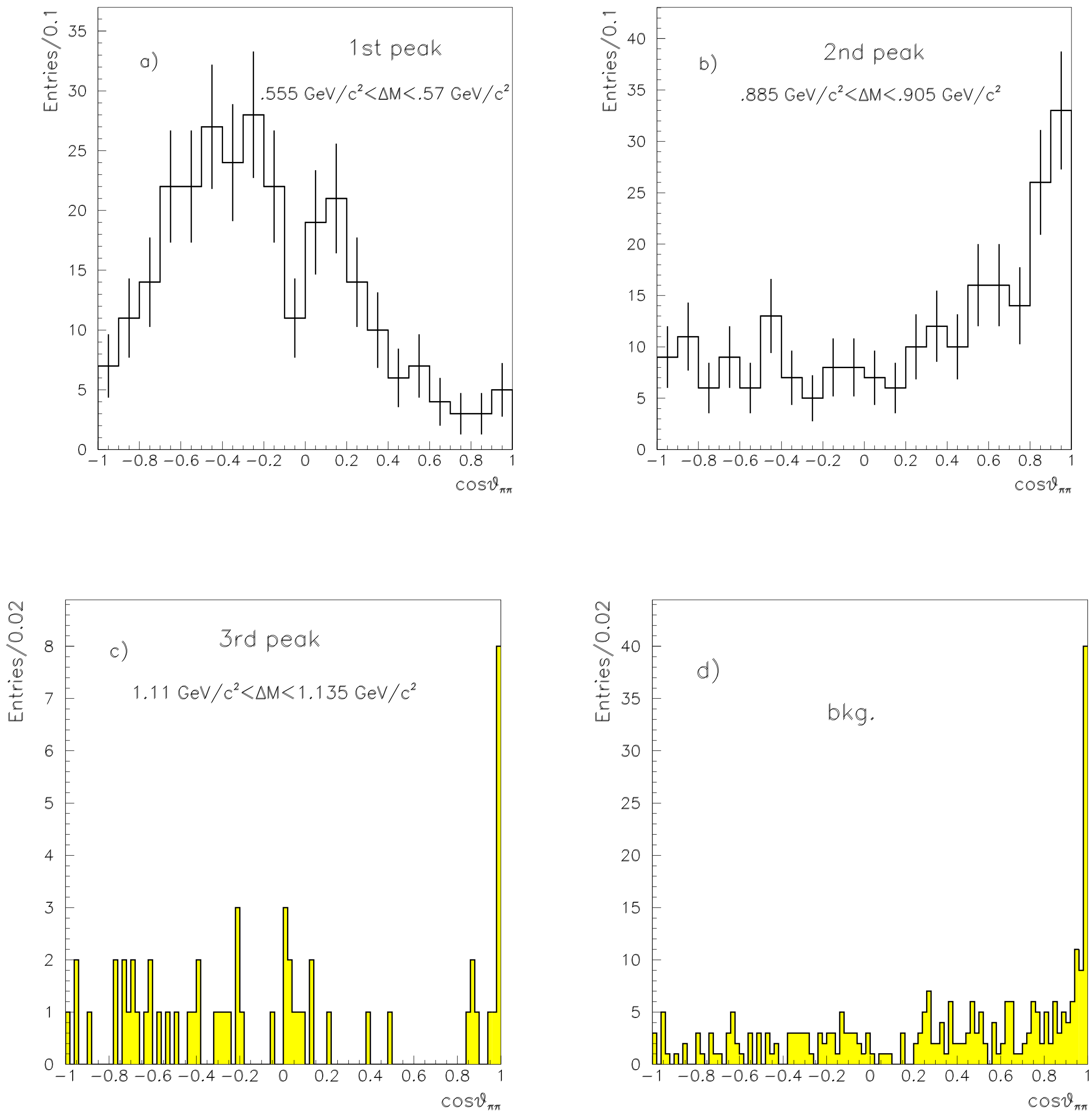

FIG. 4: The $\cos\theta_{\pi\pi}$ distributions for events from the three observed peaks and background.

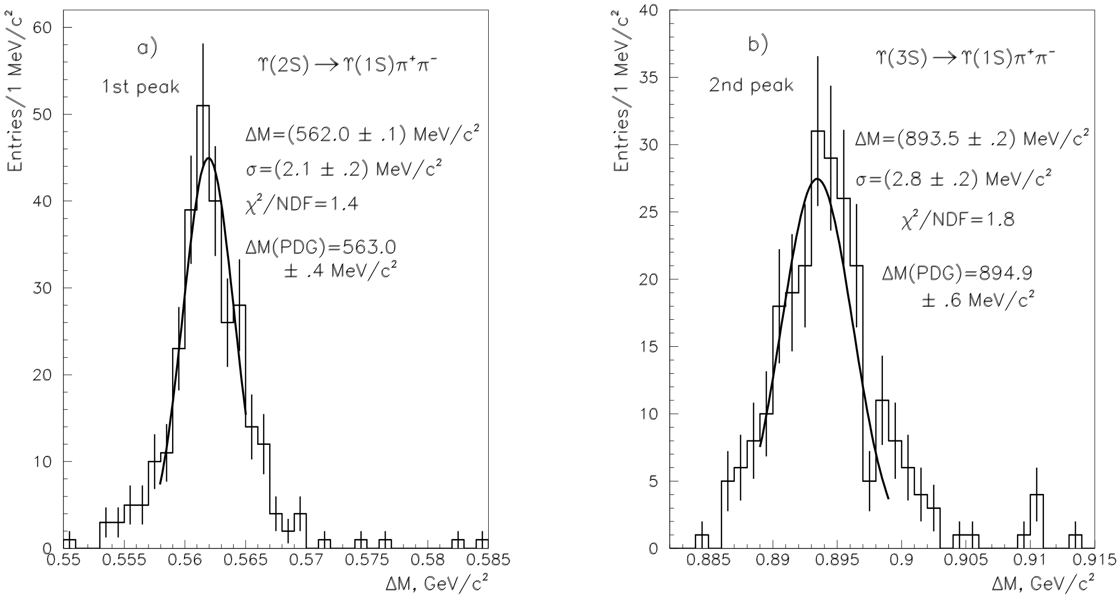

FIG. 5: The mass difference $\Delta M = (M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ distribution for the first (a) and second (b) peak ($|M_{\mu^+\mu^-} - M_{\Upsilon(1S)}|$<6 MeV/$c^2$). The central parts of the peaks are fitted by Gaussian functions.

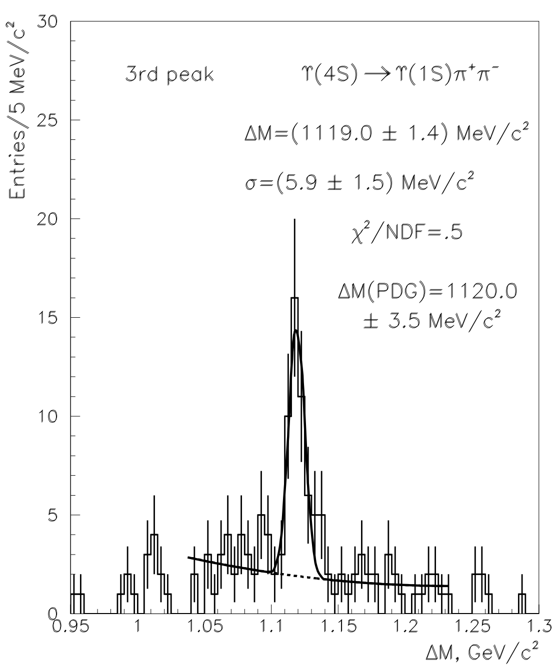

FIG. 6: The fit to the third peak in the mass difference $\Delta M = (M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ distribution ($|M_{\mu^+\mu^-} - M_{\Upsilon(1S)}|$<6 MeV/$c^2$) using the sum of a Gaussian and polynomial function.

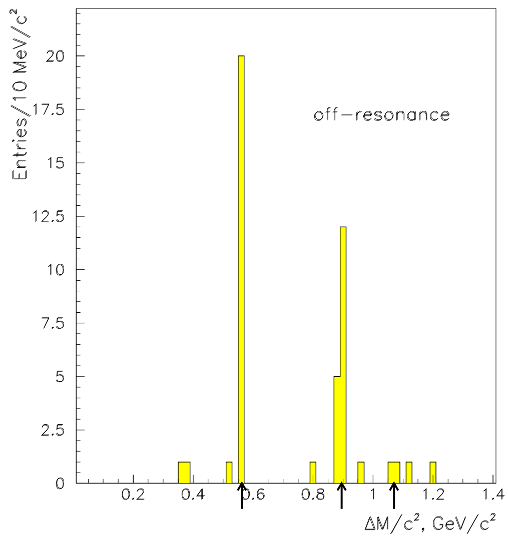

FIG. 7: The mass difference $\Delta M = (M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-})$ distribution for the off-resonance $\mu^+\mu^-\pi^+\pi^- X$-sample ($|M_{\mu^+\mu^-} - M_{\Upsilon(1S)}|$<6 MeV/$c^2$).

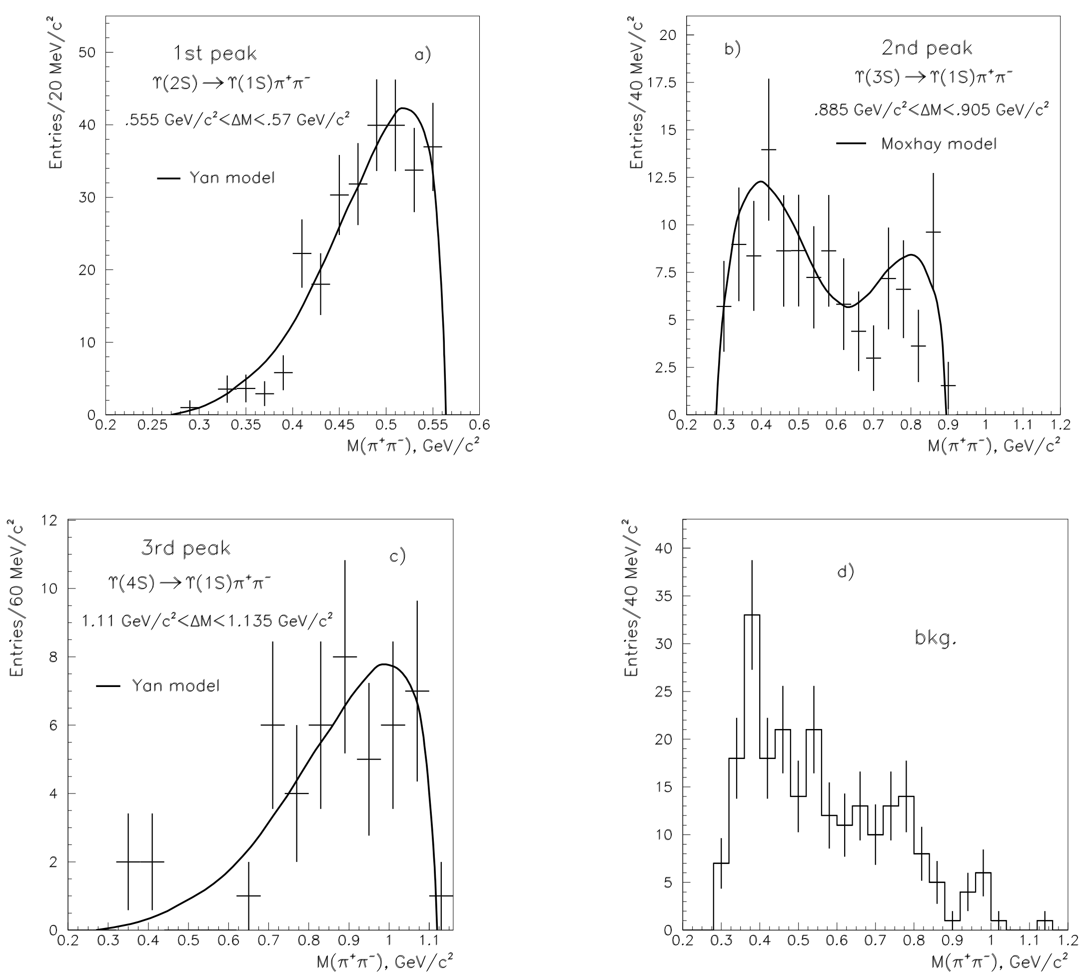

FIG. 8: The $\pi^+\pi^-$ invariant mass distributions for events from the observed peaks and background.